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Watershed-scale impacts of bioenergy crops on hydrology and water quality using improved SWAT model

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Abstract

Cellulosic bioenergy feedstock such as perennial grasses and crop residues are expected to play a significant role in meeting US biofuel production targets. We used an improved version of the Soil and Water Assessment Tool (SWAT) to forecast impacts on watershed hydrology and water quality by implementing an array of plausible land-use changes associated with commercial bioenergy crop production for two watersheds in the Midwest USA. Watershed-scale impacts were estimated for 13 bioenergy crop production scenarios, including: production of *Miscanthus* × *giganteus* and *upland Shawnee* switchgrass on highly erodible landscape positions, agricultural marginal land areas and pastures, removal of corn stover and combinations of these options. Water quality, measured as erosion and sediment loading, was forecasted to improve compared to baseline when perennial grasses were used for bioenergy production, but not with stover removal scenarios. Erosion reduction with perennial energy crop production scenarios ranged between 0.2% and 59%. Stream flow at the watershed outlet was reduced between 0 and 8% across these bioenergy crop production scenarios compared to baseline across the study watersheds. Results indicate that bioenergy production scenarios that incorporate perennial grasses reduced the nonpoint source pollutant load at the watershed outlet compared to the baseline conditions (0–20% for nitrate-nitrogen and 3–56% for mineral phosphorus); however, the reduction rates were specific to site characteristics and management practices.

Keywords: bioenergy production, corn stover, environmental impacts of bioenergy, impacts of bioenergy, *Miscanthus*, SWAT Model, Switchgrass

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Introduction

Bioenergy crop production has been discussed globally as an alternative fuel source with the concurrent benefits to reduce greenhouse gas emissions and improve water quality, specifically with cellulosic feedstock sources including perennial grasses. However, these discussions also include concerns over increased water use (Vanloocke *et al.*, 2010; Phong *et al.*, 2011) and reduced soil productivity potential due to intensive agricultural practices and removal of crop residues (Costello *et al.*, 2009; Thomas *et al.*, 2011; Cibin *et al.*, 2012; Demissie *et al.*, 2012). In the United States (US), the Energy Independence and Security Act (EISA-2007) mandates production of 136 billion liters of ethanol per year by 2022, but deployment of bioenergy cropping systems at this scale can have unknown environmental impacts. In 2010, the US Department of Agriculture (USDA) estimated that approximately 11 million hectares of cropland are needed to achieve the EISA biofuel target (USDA – 2010) and has suggested perennial grasses such as *Miscanthus* (*Miscanthus* × *giganteus*) and switchgrass (*Panicum virgatum* L.) as future energy crops capable of meeting production targets. Changes in land use and management practices associated with biofuel production scenarios, such as removal of crop residues and insertion of dedicated energy crops into farming systems, can potentially affect both the quality and quantity of water resources. For this reason, management decisions need to be carefully evaluated to quantify the environmental impact of various biofuel production practices.

Using mathematical models is ideal for analyzing impacts of future scenarios provided underlying processes are well represented in the model. The Soil and

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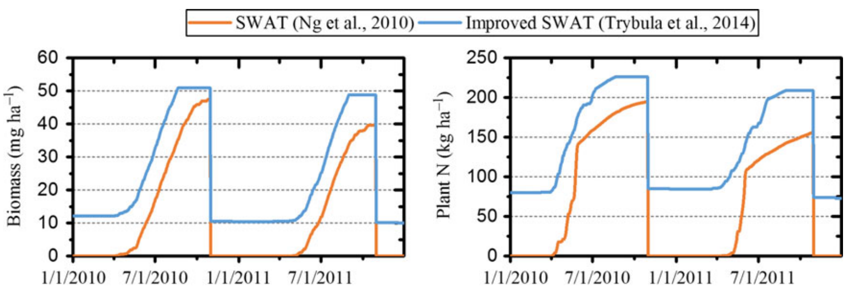
Water Assessment Tool (SWAT) (Arnold *et al*., 1998) is an established watershed model that has been identified as a potential tool for evaluating impacts of biofuel-related scenarios (Engel *et al*., 2010). However, many bioenergy crops including *Miscanthus* and switchgrass have yet to be widely implemented in commercial agriculture and are not well represented in SWAT and other similar watershed models. Accurate representation of bioenergy crop phenology in SWAT requires specific crop growth parameters for perennial grasses and revision of model algorithms for crop growth and management. Recent efforts to represent energy crops in SWAT, with exception to Trybula *et al*.(2014), used either calibrated crop growth parameters (Ng *et al*., 2010) derived from other crop model simulations, such as BioCro (Miguez *et al*., 2012), or used parameters from other crops available in the crop database of the model (Love & Nejadhashemi, 2011; Parajuli, 2012). However, as in any complex hydrologic/water-quality model, when a process representation is taken from one model and put in another, the results obtained may be considerably different due to interactions among many parameters and processes. Therefore, it is important to (re)validate the model parameters and underlying algorithms. We believe that the evidence-based parameter values directly validated in the revised SWAT model improves our confidence in the model results. Currently, limited information on crop growth validation for SWAT model exists in the literature, especially for perennial bioenergy crops, such as switchgrass and *Miscanthus*. A lack of such validation may lead to potential misrepresentation of these crops in model without considering the processes affecting perennial grass growth, such as nutrient translocation, storage of nutrients in belowground biomass during dormancy and extended evapotranspiration periods due to indeterminate growth of perennial grasses. These factors can have significant impacts on crop water and nutrient uptake processes and subsequently on hydrology and water quality.

The SWAT model simulation comparison (Fig. 1) of *Miscanthus* using the parameters from Ng *et al*. (2010) and the improved SWAT model from Trybula *et al*. (2014) indicates that changes in the model code and field data based parameterization significantly improved the biophysical representation of perennial bioenergy crops in the model. The improved model represented the belowground biomass and nutrient storage during dormancy better than the default model used thus far. These factors affected plant nutrient uptake simulation and had significant impacts on the biomass yield, hydrology and water-quality simulation (Fig. 1). A detailed comparison of perennial bioenergy crop simulations from different SWAT model representations of perennial grasses (Ng *et al*., 2010; Love & Nejadhashemi, 2011; Parajuli, 2012; Trybula *et al*., 2014) is included in supplementary information (SI). This study used the improved SWAT model (Trybula *et al*., 2014) which had better biophysical representation of perennial grasses and was parameterized and validated for bioenergy crop growth with measured data collected from nearby research plots representative of watershed conditions. Our objective was to estimate potential impacts of plausible bioenergy scenarios on watershed hydrology and water quality. The specific objectives of the research were to (1) develop plausible bioenergy scenarios for Midwest US watersheds and (2) evaluate potential environmental impacts of the plausible bioenergy crop scenarios using the improved SWAT model.



Miscanthus parameters from	Water yield (mm)	Sediment yield (kg ha^{-1})	Total nitrogen yield (kg ha^{-1})	Total Phosphorus yield (kg ha^{-1})	Biomass yield (Mg ha^{-1})
Trybula *et al*., 2014	408.7	14	8.5	0.036	24.2
Ng *et al*., 2010	187.2	20	4.4	0.057	29.1

Fig. 1 Comparison of Miscanthus simulation using improved SWAT model (Trybula *et al*., 2014) with other published SWAT model representation (Ng *et al*., 2010). The table in figure shows the annual average water, sediment, total nitrogen, total phosphorus and biomass yield with the two representations. A detailed comparison is provided in Appendix S2.

Materials and methods

The SWAT model (Arnold *et al*., 1998) was used to quantify the impacts of biofuel scenarios on hydrology and water quality at the watershed scale for two watersheds located in the Midwest USA; (1) Wildcat Creek watershed (drainage area of 2,083 km^2) located in northcentral Indiana and (2) St. Joseph River watershed (drainage area of 2,809 km^2) located in Indiana, Ohio and Michigan (Fig. 2). The two watersheds were selected to contrast the impacts of bioenergy production on a flat heavily row cropped watershed (Wildcat Creek) and flat to hilly terrain mixed land-use watershed (St. Joseph River). SWAT is a process-based, semidistributed, watershed-scale model. The model divides a watershed into hydrologic response units (HRUs) within subwatersheds. HRUs, SWAT's smallest spatial unit for simulation, are areas with unique combinations of land use, soil type and slope. A detailed description of SWAT can be obtained from Neitsch *et al*. (2005).

Thirteen biofuel crop production scenarios were formulated (Table 1) considering bioenergy crop production (1) on highly erodible soils (Scenarios 1 and 2); (2) on agriculturally marginal lands (Scenarios 3 and 4); (3) with stover removal from low-slope areas (Scenario 5); (4) with bioenergy crops planted on current pasture areas (Scenario 6 and 7); and their combinations (Scenarios 8–13). *Miscanthus* (*Miscanthus* × *giganteus*) and Shawnee, an upland switchgrass (*Panicum virgatum L.*) variety, were included as dedicated bioenergy crops and corn (*Zea mays* L.) stover as crop residue for biofuel production (70% mass removal rate, Cibin *et al*., 2012). The corn and soybean (*Glycine max* L. Merril) areas with >2% slope were considered as potential highly erodible areas. Agricultural marginal lands were defined as areas where simulated corn productivity compared to the 14-year baseline simulated average for the watershed was less than the 5th percentile. The 70% stover removal represents potential stover that can be collected from shredding, raking and baling (Brechbill & Tyner, 2008).

A calibrated and validated SWAT model [SWAT version 615 which includes improved perennial crop simulation (Trybula *et al.* (2014)] for the two watersheds were used to quantify impacts of 13 biofuel scenarios described above. The calibrated/validated model representing current agricultural land use is considered as the baseline scenario. Weather data for 14 years (1996–2009) was used to predict long-term hydrology and water-quality impacts of the thirteen bioenergy scenarios.

Study area description and SWAT model representation

Wildcat Creek watershed (WCC) is a relatively flat terrain (88% area <2% slope) and is predominantly agricultural with 70% of the total land in corn/soybean rotation and 5% in pasture (United States Department of Agriculture-National Agricultural Statistics Services, 2009). St. Joseph River (SJR) watershed is flat to hilly terrain (40% area >2% slope) and is mixed land use with 37% corn/soybean rotation, 25% pasture, 12% forest, 10% developed area and 8% forested wetlands. The SWAT model for both study watersheds were developed as methodology discussed in Cibin *et al.* (2012) and was calibrated/validated for crop growth, stream flow and water quality (sediment, nitrate-nitrogen and total phosphorus) using basin-level model

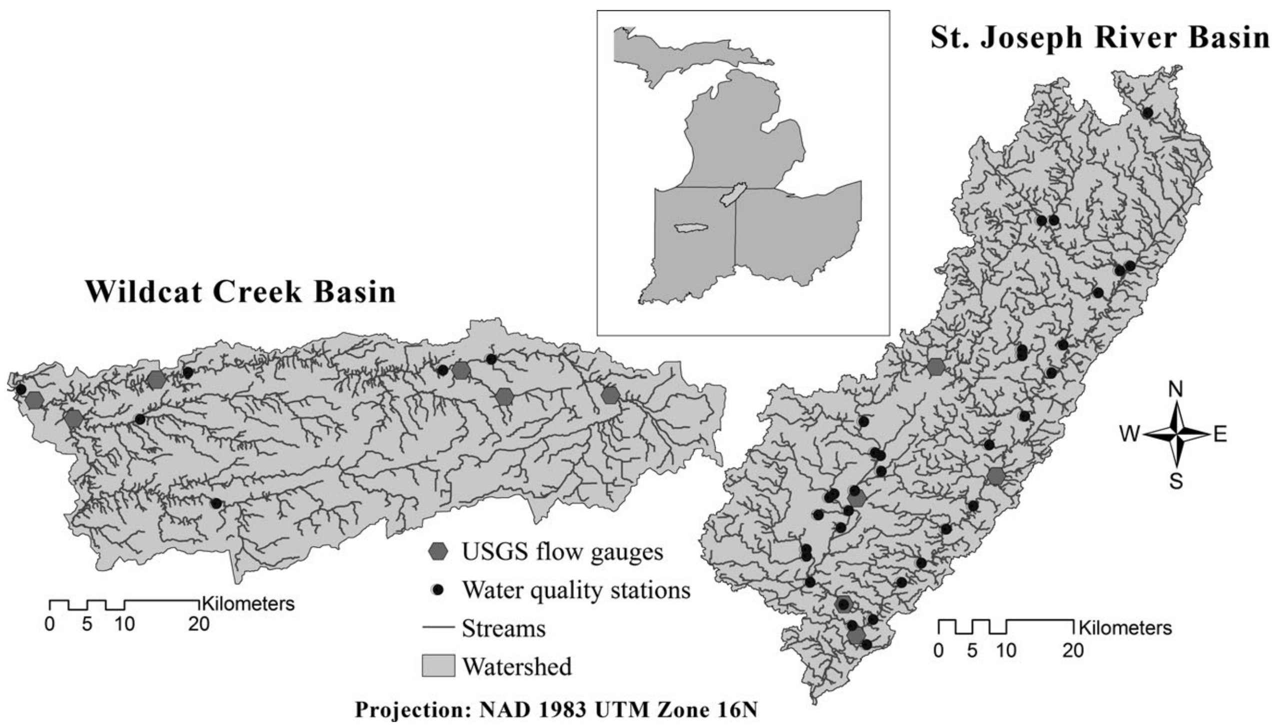


Fig. 2 Location map of Wildcat Creek watershed and St Joseph River watershed.

Table 1 Biofuel scenarios evaluated using the improved Soil and Water Assessment Tool (SWAT). Baseline scenario describes current agricultural land use in the study watersheds, predominantly corn/soybean (CS). Scenarios are developed as listed below by changing corresponding agricultural land use from the baseline into *Miscanthus* × *giganteus* (*Misc*), upland ecotype *Panicum virgatum L.* (switch) and/or corn residue removal at harvest (70% of stover present at grain harvest)

					Wildcat Creek (2,083 km^2)			St Joseph River (2,809 km^2)		
Scenario	Pasture	<2% slope CS area*	>2% slope CS area*	<5%ile yield CS area†	Energy crop area (km^2)	N Fert‡ (Kg ha^{-1})	P Fert‡ (Kg ha^{-1})	Energy crop area (km^2)	N Fert‡ (Kg ha^{-1})	P Fert‡ (Kg ha^{-1})
Baseline	–	–	–	–	0	63.6	19.2	0	46.7	11.3
Scenario 1	–	–	*Misc*	–	120	61.9	17.6	347	42.9	8.0
Scenario 2	–	–	Switch	–	120	61.9	17.6	347	42.9	8.0
Scenario 3	–	–	–	*Misc*	60	62.8	18.4	119	45.4	10.2
Scenario 4	–	–	–	Switch	60	62.8	18.4	119	45.4	10.2
Scenario 5	–	stover	–	–	0	79.2	22.2	0	50.3	12.0
Scenario 6	*Misc*	–	–	–	102	63.6	18.9	710	46.7	10.1
Scenario 7	Switch	–	–	–	102	63.6	18.9	710	46.7	10.1
Scenario 8	*Misc*	–	*Misc*	–	222	61.9	17.4	1057	42.9	6.8
Scenario 9	Switch	–	Switch	–	222	61.9	17.4	1057	42.9	6.8
Scenario 10	*Misc*	stover	*Misc*	–	222	77.4	20.4	1057	46.5	7.5
Scenario 11	Switch	stover	Switch	–	222	77.4	20.4	1057	46.5	7.5
Scenario 12	*Misc*	stover	*Misc*	*Misc*	263	76.3	19.7	1136	45.2	6.6
Scenario 13	Switch	stover	Switch	Switch	263	76.3	19.7	1136	45.2	6.6

*Study criteria for highly erodible land.
†Study criteria for agricultural marginal land.
‡Whole watershed average fertilizer application.

parameters as discussed in Cibin & Chaubey (2015) (SI Table S3). A detailed description of SWAT model development, calibration and validation is provided in supplementary information. The SWAT model calibration/validation evaluation indices for daily stream flow and water-quality simulations for the both watersheds (Appendix S1) were well above acceptable ranges recommended by many researchers (Engel *et al.*, 2007; Moriasi *et al.*, 2007).

Biofuel scenarios representation in the SWAT model

The SWAT model requires about 25 crop growth parameters to represent plant emergence, biomass production and partitioning, leaf area and canopy development, water and nutrient uptake, and maturity definitions. This study used crop growth parameters (SI Table S7) derived by Trybula *et al.*(2014) from field measurements for *Miscanthus* and Shawnee switchgrass at the Purdue Water Quality Field Station (WQFS) located in northcentral Indiana near WCC. Trybula *et al.* (2014) also improved SWAT crop model algorithms to better represent bioenergy production of perennial grasses. The evidence-based parameterization and model code improvements enhanced the physical representation of perennial grass growth for biomass production, nutrient uptake and nutrient translocation/storage in model simulations, which improved hydrologic and water-quality outputs. The model improvements are included in release version of SWAT model (version 615 and beyond). Additional detailed information about model parameterization and improvements are provided in Trybula *et al.* (2014).

Miscanthus, switchgrass and pasture grasses were represented in the model as multiyear crop rotations, with planting in the first year of simulation only. Tall fescue (*Schedonorus arundinaceus* (Schreb.) Dumort) was selected in this study for pasture management with rotational grazing and hay cut. A detailed discussion of pasture and other crop management practices is provided in Appendix S1. *Miscanthus* and switchgrass were planted on April 1, and tall fescue was planted on March 1. Perennial crop emergence after dormancy was triggered in subsequent years by average daily air temperature above the crop base temperature. Crop management practices were the same for *Miscanthus* and switchgrass, including fertilizer application of 56 kg-N ha^{-1} in the form of urea and an October 31 harvest date, as practiced at the WQFS (Trybula *et al.*, 2014). The first 4 years of model simulation were considered in the model warm-up period to stabilize initial conditions in the model. Perennial energy crops have a recognized period of establishment in the first 3–4 years of grass development; at present, the SWAT model is not capable to represent the establishment phase for perennial grasses. SWAT model for this study was designed to include this establishment period of perennial grasses during the model warm-up; in effect, the study results discussed for perennial grasses are with fully established stands of *Miscanthus*, switchgrass and tall fescue. Corn stover removal was represented in SWAT as 70% stover biomass removal after corn grain harvest. Stover removal scenarios included additional fertilizer application at the rate of 7.95 kg anhydrous ammonia and 2.85 kg P_2O_5 per tonne or Mg of stover removed to account for nutrient replacement (Brechbill & Tyner, 2008).

Results and discussion

Simulated yields of bioenergy crops on erodible (>2% slope) nontiled corn/soybean areas averaged 20.6 and 18.3 Mg ha^{-1} for *Miscanthus* and 10.9 and 10.2 Mg ha^{-1} for switchgrass, respectively, for WCC and SJR watersheds. Simulated yields were similar to measured yields of 25 and 10 Mg ha^{-1} for *Miscanthus* and switchgrass, respectively, at the WQFS (Burks, 2013), considering the climate variability across simulation period, differences in soil and slope at WQFS and the WCC watershed. SJR watershed further north of WCC crop yields were generally lower compared to WCC due to relatively lower temperature, growing period and land quality. SJR has more highly erodible and agricultural marginal lands compared to WCC (Table 1). The corn stover harvested yield was estimated to be 7.3 and 5.9 Mg ha^{-1} with 70% stover removal rate from low-slope tiled areas in WCC and SJR, respectively. The 5th percentile corn yield for identifying agricultural marginal land was estimated as 8 Mg ha^{-1} (5.5 Mg ha^{-1} for SJR) for the WCC watershed from SWAT model simulations; HRUs with <5 percentile corn yield were considered as agriculturally marginal land for Scenarios 3, 4, 12 and 13. The average biomass yield from agricultural marginal land (18.6 and 9.8 Mg ha^{-1} for *Miscanthus* and switchgrass, respectively, for WCC) was less than yield from highly erodible soils. Table 2 shows the ethanol production potential for the scenarios, considering ethanol potential as 473 l per Mg for corn stover and 403 l per Mg for energy crop feedstock obtained from a theoretical ethanol yield (http://www.afdc.energy.gov/fuels/ethanol_feedstocks.html). Biofuel production potentials for the WCC watershed with *Miscanthus* were estimated as 83, 97 and 45 million liters when placed in pasture, highly erodible and agriculturally marginal areas, respectively. The two watersheds combined could produce approximately 1.4 billion liters of ethanol with Scenario 12 which represents stover removal from low erodible soil and *Miscanthus* grown in pasture, highly erodible and agriculturally marginal lands.

Impacts of biofuel crop production scenarios

Impacts on hydrology. Stream flow at the watershed outlet was slightly reduced under biofuel production scenarios (Table 2). The percentage reduction in stream flow ranged from 0.2% (Scenario 7) to 4.5% (Scenario 12) for WCC and 0.3% (Scenario 3) to 7.9% (Scenario 12) for SJR watershed (Fig. 3). In general, the reduction in stream flow was slightly more for *Miscanthus* than switchgrass. In Scenario 13, 40% area land-use change and 25% area land-management change (stover removal) in SJR induced only 3% reduction in stream flow for SJR watershed, which indicates minimal impacts on blue water footprint with switchgrass and stover removal based scenarios. A detailed monthly analysis to better understand different hydrologic processes resulting from bioenergy-driven land-use changes (corn/soybean and pasture to energy crops) was performed for two sample HRUs in the WCC watershed, one corn/soybean and one pasture HRU

Table 2 Average annual impact of biofuel scenarios on predicted stream flow, sediment losses and water quality at Wildcat Creek and St Joseph River watershed outlets. Biofuel potential calculated considering a theoretical ethanol yield of 473 l per Mg of corn stover and 403 l per Mg of energy crop feedstock

	Wildcat Creek watershed					St Joseph River watershed				
	Flow (m^3 s^{-1})	Sediment (Mg ha^{-1})	Nitrate (kg ha^{-1})	Min P (kg ha^{-1})	Biofuel potential ($\times 10^6$ l)	Flow (m^3 s^{-1})	Sediment (Mg ha^{-1})	Nitrate (kg ha^{-1})	Min P (kg ha^{-1})	Biofuel potential ($\times 10^6$ l)
Baseline	25.95	1.04	18.89	0.37	0	31.27	0.22	7.42	1.04	0
Scenario 1	25.56	0.69	18.75	0.31	97	30.28	0.10	7.13	0.51	256
Scenario 2	25.82	0.69	18.77	0.31	52	30.75	0.10	7.16	0.51	143
Scenario 3	25.82	1.01	18.44	0.34	45	31.02	0.16	7.17	0.96	86
Scenario 4	25.92	1.01	18.60	0.34	24	31.17	0.16	7.39	0.96	46
Scenario 5	25.36	1.13	17.96	0.36	229	31.01	0.23	6.54	1.06	98
Scenario 6	25.73	1.04	18.86	0.36	83	30.18	0.22	7.29	1.01	542
Scenario 7	25.96	1.04	18.88	0.36	45	31.15	0.22	7.35	1.00	295
Scenario 8	25.35	0.69	18.72	0.31	180	29.19	0.10	7.00	0.48	797
Scenario 9	25.83	0.69	18.75	0.31	97	30.62	0.10	7.09	0.48	438
Scenario 10	24.76	0.78	17.79	0.31	409	28.92	0.11	6.11	0.50	895
Scenario 11	25.24	0.78	17.82	0.30	326	30.36	0.11	6.21	0.50	536
Scenario 12	24.68	0.76	17.42	0.29	433	28.79	0.09	5.94	0.46	943
Scenario 13	25.23	0.76	17.59	0.29	336	30.33	0.09	6.25	0.46	557

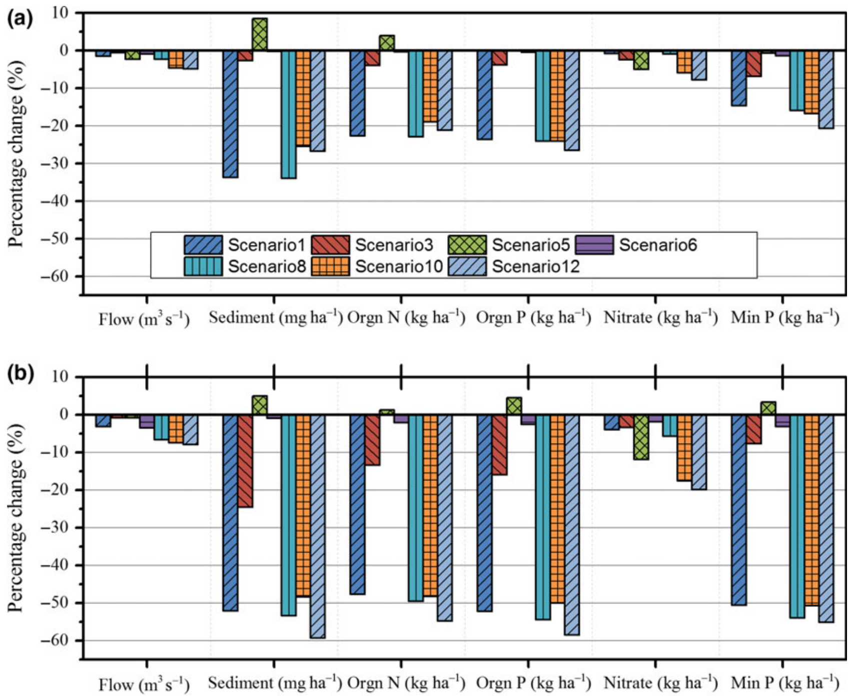


Fig. 3 Average annual impact of *Miscanthus*-based biofuel scenarios on stream flow and water quality at the watershed outlet. (a) Wildcat Creek watershed (b) St Joseph River watershed. Positive value indicates increase in value with respect to baseline scenario.

with the same climate region and soil type. The monthly analysis for both corn/soybean and pasture changing to energy crops shows more reduction in surface runoff with *Miscanthus* compared to switchgrass (Fig. 4a), possibly due to higher evapotranspiration and soil moisture reduction for *Miscanthus* when compared to switchgrass. The study used SCS curve number (SCS, 1972) method to estimate surface runoff from field units, and it should be noted that the same initial curve number (CN) was assumed for both energy crops. The model updates CN on a daily basis with soil moisture and residue cover. The simulated reduction in surface runoff was more with corn/soybean than pasture changing to a perennial grass energy crop (Fig. 4a). The reduction in surface runoff for perennial energy crops compared to annual crops was predominant in the months of June and July when the crops are fully mature and perennials have better soil cover compared to row cropped annuals. Surface runoff from pasture area was high in the months of June to August compared to perennial energy crops due to summer grazing of pasture area.

A prolonged growing season resulted in increased evapotranspiration from energy crops during the growing season (months 9 to 10; Fig. 4b) compared to corn/soybean. Previous field studies also reported similar increases in evapotranspiration for *Miscanthus* and switchgrass compared to corn/soybean (Hickman *et al*., 2010; McIsaac *et al*., 2010). Pasture areas simulated to have low evapotranspiration during growing season (months 6 to 8; Fig. 4b) compared to energy crops, which could be attributed to pasture management representation such as hay harvest in May and summer grazing. Nongrowing season (November–April) evapotranspiration dominated by soil evaporation for both energy crops was lower than corn/soybean and pasture (Fig. 4b), potentially due to a reduction in soil moisture with energy crops at the final stages of growth period (September–October) (Fig. 4c). Field trials from McIsaac *et al.* (2010) also reported similar reduced moisture content with *Miscanthus* in later stages of growing season compared to corn/soybean. The changes in soil moisture and evapotranspiration affect the subsurface flows (lateral, tile and ground water flow); thus, in general, reduction in water yield for *Miscanthus* was slightly more than switchgrass (Fig. 4d). Subsurface flow generally increased with perennial grasses compared to baseline corn/soybean rotation (Table S8), this reduces peak flows and improves low flow conditions and could be attributed toward increased infiltration and soil moisture content with perennials. Tile flow measured using undisturbed lysimeters at WQFS demonstrated reduction in drainage event volume with cropping system transition from corn/soybean to *Miscanthus* similar to current study results, while switchgrass response varied across replicates (Trybula, 2012). Residue removal scenarios also predicted reduced stream flow at the watershed

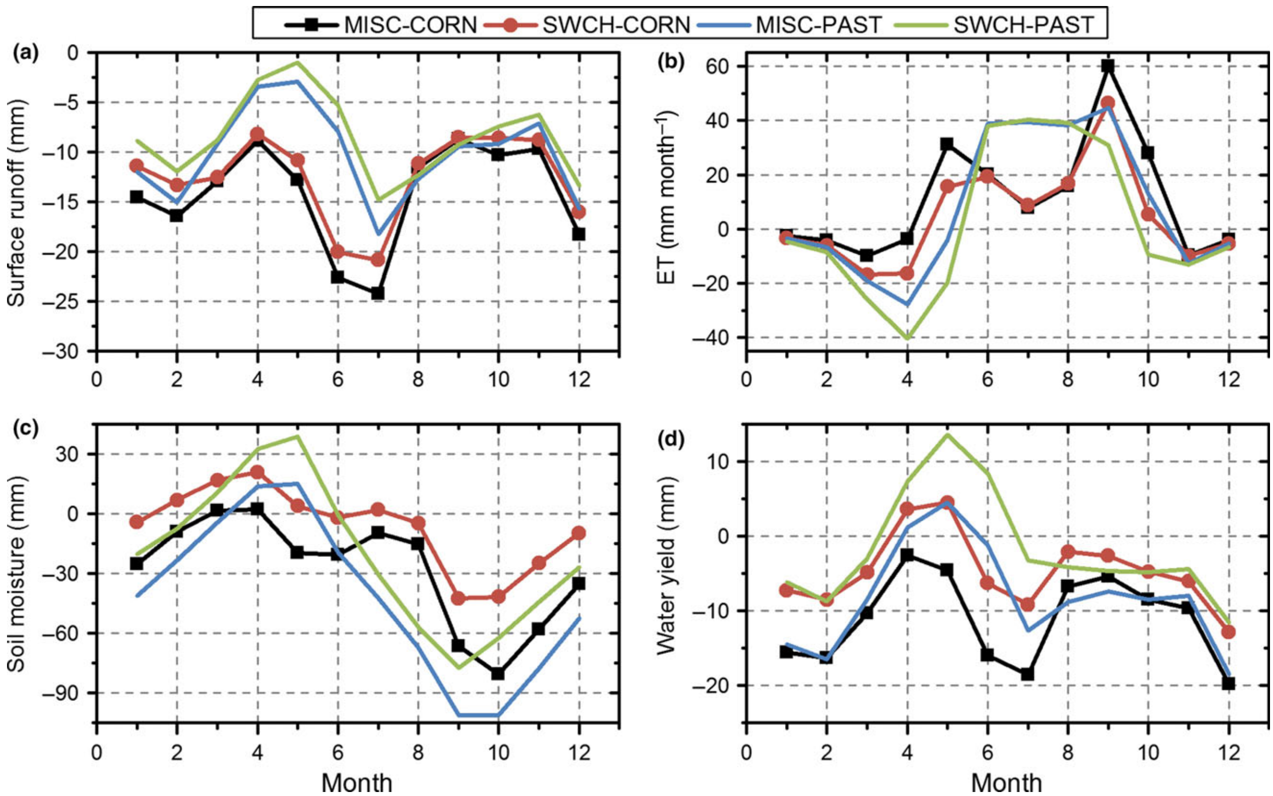


Fig. 4 Monthly analysis of energy crop impacts on various hydrology components in one corn/soybean and pasture HRU. Difference with corn/soybean changed to *Miscanthus* (MISC-CORN) and switchgrass (SWCH-CORN) and difference with pasture HRU changing to *Miscanthus* (MISC-PAST) and switchgrass (SWCH-PAST) for monthly surface runoff (a), evapotranspiration (b), soil moisture (c) and water yield (d). A positive value indicates the energy crop scenario values are higher than baseline scenario.

outlet, which may be caused by increased evaporation from loss of soil cover (van Donk *et al.*, 2010; Cibin *et al.*, 2012) during the nongrowing season. Residue removal also tends to reduce the water-holding capacity of soil (van Donk *et al.*, 2010).

Impacts on erosion. Sediment loading at watershed outlet decreased with biofuel scenarios, with the exception of the stover removal (Table 2). Erosion reduction was expected for land-use change from annual row crops to perennial bioenergy crops (Self-Davis *et al.*, 2003; Parrish & Fike, 2005). Erosion rates predicted for both *Miscanthus* and switchgrass scenarios were nearly identical. This may be associated with same Modified Universal Soil Loss Equation (MUSLE) crop factor used for both energy crops. The percentage reduction in sediment loading with bioenergy crops ranged from 0.2% for scenario 7 in WCC to 59.4% for scenario 12 in SJR (Fig. 3). The 70% corn stover removal scenario showed an increase in erosion and sediment loading as compared to the baseline. This potential increase in soil erosion with residue removal is a major concern for biofuel production (Delgado, 2010; van Donk *et al.*, 2010; Johnson *et al.*, 2010; Cibin *et al.*, 2012). Perennial energy crops in highly erodible area (5.8% and 12.3% of total WCC and SJR watershed area, respectively) reduced sediment loading at watershed outlet by 34% and 52% for WCC and SJR, respectively. The erosion reduction with energy crops in highly erodible areas for a relatively flat watershed such as WCC indicates the general opportunity of growing bioenergy crops as potential best management practice for reducing erosion. Monthly analysis (Fig. 5a) shows a consistent reduction in predicted soil erosion when corn/soybean cropping systems are changed to perennial energy crops, while predicted erosion rates for both pasture and perennial energy crops were similar. Another factor affecting soil erosion could be a lack of annual land preparation practices typically associated with many of the annual crops. The land-management practices such as tillage and fertilizer application in corn/soybean areas could change with stover removal implementation by farmers to minimize impacts; the current study accounted the possible increased fertilization with stover removal (SI Tables S1 and S5) while the tillage practices were represented same for with and without stover removal.

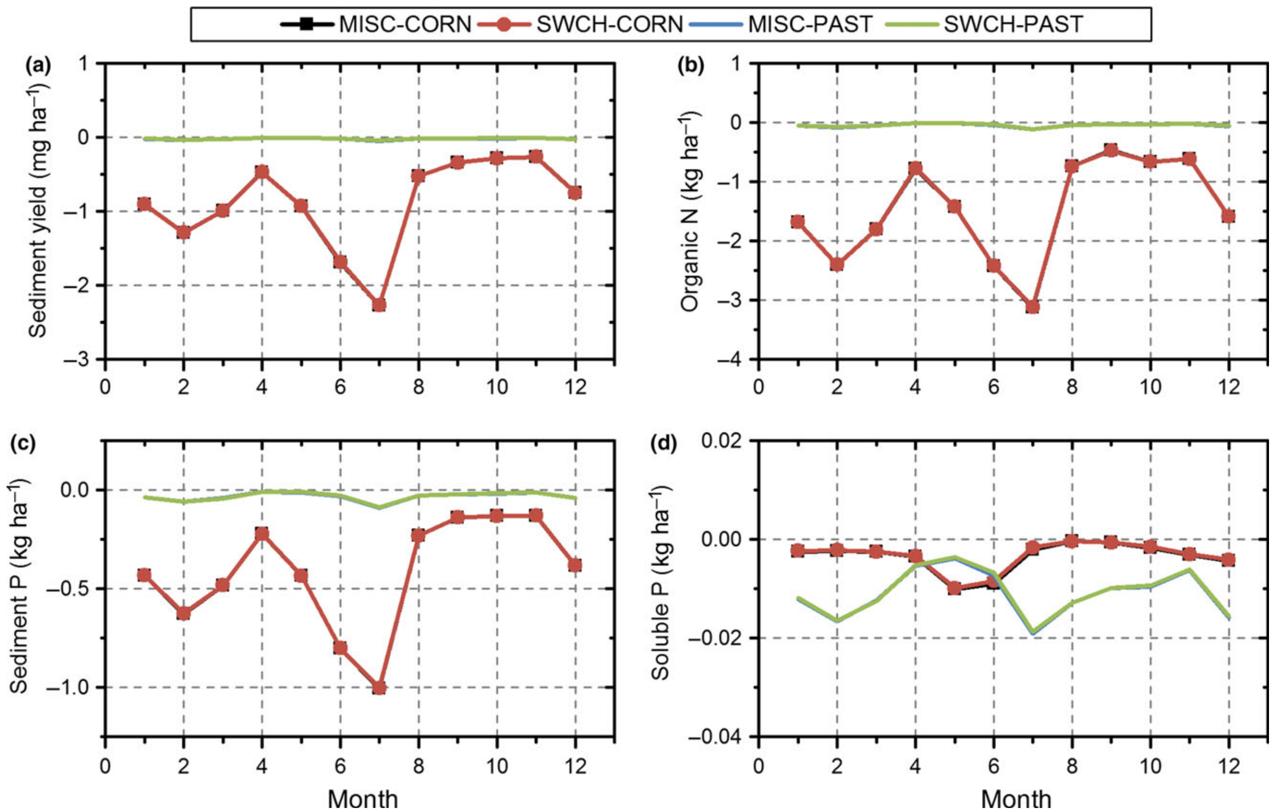


Fig. 5 Monthly analysis of energy crop impacts on sediment (a), organic N (b), sediment P (c) and soluble P (d) in one corn/soybean and pasture HRU. Difference with corn/soybean changed to *Miscanthus* (MISC-CORN) and switchgrass (SWCH-CORN) and difference with pasture HRU changing to *Miscanthus* (MISC-PAST) and switchgrass (SWCH-PAST). A positive value indicates the energy crop scenario values are higher than baseline scenario. (MISC-CORN) and (MISC-PAST) are not visible in some figures as *Miscanthus* and switchgrass simulations were very similar.

Impacts on nutrient losses. In general, the model simulations indicate that biofuel crop production will likely reduce nutrient losses compared to current cropping systems used in this watershed. The rate of reduction varies with the areal extent of deployment and type (perennial grass vs. stover) of bioenergy crop grown. The trend in nutrient loss reduction is highly correlated with sediment loading for adsorbed nutrients (organic N and P) and with stream flow for nutrients transported in dissolved form (nitrate and soluble P) (Fig. 3).

As expected, the reductions and trends in adsorbed nutrient losses were similar to that of sediment losses (Fig. 5). Organic N reduction ranged from 0.2% to 23% for WCC and 1.8% to 55% for SJR watershed, similarly, organic P reduction ranged from 0.4% to 26.4% and 2.2% to 59%, respectively, for both watersheds. Organic N and P loadings for pasture and energy crops were similar, and reductions were similar for *Miscanthus* and switchgrass for all other scenarios. The stover removal scenario showed 3.1% and 1.2% increase in organic N and 1.6% reduction and 4.5% increase in organic P loading for WCC and SJC, respectively.

Annual nitrate loading trend was very similar to the stream flow trend for bioenergy scenarios. The nitrate reduction from stover removal was found to be more prominent than reduction with the perennial grass scenarios. In general, *Miscanthus* scenarios showed slightly higher reduction in nitrate loading (Fig. 3) than switchgrass scenarios (Fig. S13) at the watershed outlet. This difference in nitrate loading from *Miscanthus* and switchgrass may be due to higher simulated nitrogen uptake by *Miscanthus* compared to switchgrass (Table S8), both crop scenarios received the same fertilizer application rates (56 kg-N ha^{-1}). Field studies also reported higher nitrogen uptake by *Miscanthus* compared to switchgrass (Heaton *et al.*, 2009; Burks, 2013). In addition, this study considered a relatively high rate of mineralization of organic nutrients for all scenarios. Humus mineralization of organic nutrients rate coefficient (CMN) of 0.003 was recommended by Trybula *et al.* (2014) to increase mineralization rates for *Miscanthus* to better represent soil characteristics at the research plots, and this value was used for all scenarios including baseline scenario in this study. The rate of

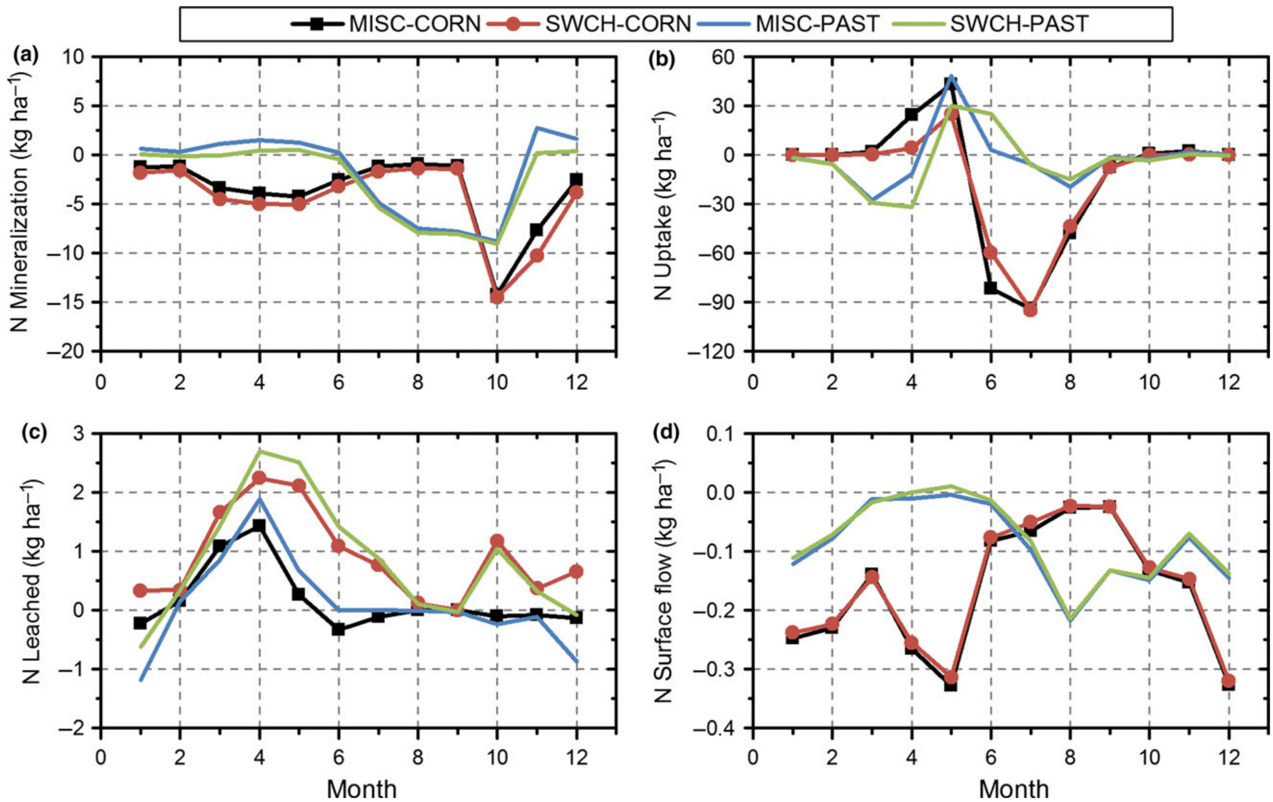


Fig. 6 Monthly analysis of energy crop impacts on various nitrogen components in one corn/soybean and pasture HRU. Difference with corn/soybean changed to *Miscanthus* (MISC-CORN) and switchgrass (SWCH-CORN) and difference with pasture HRU changing to *Miscanthus* (MISC-PAST) and switchgrass (SWCH-PAST) for monthly N mineralization (a) N uptake (b), N leached (c) and N in surface flow (d). A positive value indicates the energy crop scenario values are higher than baseline scenario.

humus mineralization could be land-use specific corresponding to their soil microclimate and associated crop-specific microorganisms (Orr, 2012; Chen *et al*., 2014). At present, the SWAT considers nonlimiting soil moisture, temperature and carbon-to-nitrogen ratio for mineralization, but the rate coefficient is a basin-level parameter uniform for all crop/soil types. Lack of measured data on mineralization rates also makes it difficult to estimate this parameter at field level leaving the option for a model user to calibrate the parameter using in-stream nitrate loading data. Further studies are required to better constrain crop-specific nutrient mineralization rates in SWAT representation and validation of mineralization.

Nitrate loading through surface runoff decreased when pasture and corn/soybean land use were converted to perennial grass energy crops (Fig. 6d). However, the impacts on subsurface nitrate losses such as nitrate leached (for nontiled areas) and tile nitrate loading varied across HRUs (Fig. S14), indicating the sensitivity of land area characteristics. The sample HRU selected for detailed analysis indicated increase in leached nitrate for both energy crops compared to baseline (Fig. 6c). Comparison of nitrate leached from all HRUs in Scenarios 1 and 2 indicates slightly over 50% of HRUs in WCC and 80% of HRUs in SJC trend toward reduction in nitrate leached with *Miscanthus* and almost 99% of WCC and 75% of SJC trend toward increased nitrate leached with switchgrass compared to baseline corn/soybean (Fig. S14). The major factors affecting nitrate leaching are the percolation rate, fertilization (application timing with precipitation and amount), soil nutrient dynamics and plant nutrient uptake. In general, percolation rate is increased with perennial grasses due to higher infiltration, while average fertilization rate, plant uptake and residue mineralization are low for energy crops comparing to annual corn/soybean rotation. The trend in leached nitrate depended on which of the above-mentioned factors are more dominant in specific HRU. The study scenarios considered only very limited tile drained area converting to bioenergy crops. The tile nitrate were generally reduced with both energy crops in WCC while simulation results from SJC indicated reduction in tile nitrate with *Miscanthus* and increase with switchgrass (Fig. S14). Field studies have reported reductions in subsurface nitrate loading with

both perennial grass energy crops (McIsaac *et al.*, 2010; Trybula, 2012). A lower total mineralization (including humus organic and fresh residue mineralization) for energy crops was predicted compared to corn/soybean and pasture (Fig. 6a). Field study conducted at side-by-side comparison of corn/soybean plots and energy crop plots also reported low net mineralization with energy crops comparing to corn/soybean (Orr, 2012). Relative to energy crops, pasture areas were simulated with high mineralization in growing season due to grazing as grazing adds extra manure and tramples grasses to soil. The literature on pasture area nutrient cycling reported increased mineralization with grazing through decomposition and excretion of plant nutrients (Bardgett *et al.*, 1997; Bardgett & Wardle, 2003) along with stimulated soil microbial activity from animal excreta (Wang *et al.*, 2006); however, the excreta is often heterogeneous and highest near shade and water sources (Iyyemperumal *et al.*, 2007). At present, SWAT cannot represent the increased microbial activity and also considers excreta manure and trampling to be uniform in grazed HRU. Simulated average annual mineralization with corn/soybean and pasture was 97 and 72 kg-N ha^{-1}, respectively, for the selected HRU, while for *Miscanthus* and switchgrass, was 53 and 43 kg-N ha^{-1}, respectively. The major component of corn/soybean and pasture mineralization was from residue organic matter representing about 70 and 47 kg-N ha^{-1}, respectively. Aboveground residues after grain harvest and belowground biomass are incorporated to soil organic pool for corn/soybean and contribute to the residue organic N pool in the model. In pasture, the biomass trampled during grazing and manure contributes toward fresh organic nitrogen pool; this difference can be visualized in growing season (July–October, Fig. 6a). In perennial energy crops, the belowground biomass acts as nutrient storage organs during dormancy period and only aboveground biomass after harvest contributes to the fresh organic residue pool, resulting in low mineralization (Fig. 6a). Dormancy period of perennial grass root decay component is not considered in this study due to lack of data to represent root decay (Trybula *et al.*, 2014). SWAT predicted nutrient uptake from soil by energy crops to be relatively low compared to corn/soybean and pasture crops. The nutrient stored in belowground biomass for perennial energy crops reduces the nutrient requirement at the early growing stages, and thus, the nutrient uptake was also simulated low for both *Miscanthus* (~100 kg-N ha^{-1}) and switchgrass (~80 kg-N ha^{-1}) compared to corn/soybean (~250 kg-N ha^{-1}) and pasture (115 kg-N ha^{-1}). Bioenergy field studies in Indiana (Burks, 2013) and Illinois (Heaton *et al.*, 2009) also reported similar ranges of nitrogen uptake for both *Miscanthus* and switchgrass. Monthly analysis indicates reduction in surface runoff nitrate loading by about 0.16 kg ha^{-1} month^{-1} with corn/soybean and about 0.08 kg ha^{-1} month^{-1} with pasture area changing to energy crops. Reduction in surface flow nitrate and increased subsurface flow nitrate loading with energy crops will necessitate implementation of conservation practices (e.g., nitrate-reducing bioreactors) to reduce subsurface nitrate losses from perennial energy crops.

The stover removal in low-slope areas of SJC and WCC simulated a 4.9% and 11.9% nitrate load reduction at watershed outlet even with 8% and 24% increased fertilizer application, respectively. The reduced residue in field after stover harvest reduced the nutrient source for mineralization which reciprocated to reduced nitrate loading with stover removal. Previous research reveals that repeated stover removal can reduce net mineralization (Kapkiyai *et al.*, 1999; Salinas-Garcia *et al.*, 2001) and reduce organic N returning to soil (Dolan *et al.*, 2006; Blanco-Canqui & Lal, 2009). A detailed discussion of stover removal impacts on hydrology and water quality with different stover removal rates for the WCC watershed can be obtained from Cibin *et al.* (2012).

Mineral P loading was reduced consistently across perennial grass scenarios (Table 2, Fig. 3), ranging from a reduction of 1.4% for scenario 6 in WCC to 56% for scenario 13 in SJC. Monthly analysis (Fig. 5c) for adsorbed P transport depicts same trend as sediment yield (Fig. 5a) for both pasture and corn/soybean changing to energy crops. Soluble P (Fig. 5d) had similar trend as that of surface runoff (Fig. 4a). Both dissolved and adsorbed P were reduced consistently across all months with energy crops.

Implications

Quantifying watershed-scale impacts of bioenergy production scenarios provides the opportunity to evaluate the potential commercial and environmental trade-offs associated with viable feedstock operations. As alternatives are considered across a variety of landscape scales, environmental managers, policymakers, industry leadership and farmers can utilize forecasted water-use needs and water-quality impacts of feedstock production scenarios in the process of decision making. In the broader context of comprehensive watershed management, this information may enable bioenergy crop production for ecosystem services restoration while reducing unintended negative consequences. Based on the results of this study, *Miscanthus* and switchgrass production may be a strong candidate for implementation in watersheds that would generally benefit from sediment and nutrient load reduction and can sustain base flows during drought conditions. Alternatively, integrated systems might harness the versatility of

stover production that can be buffered by manageable swatches of perennial grasses.

A revised SWAT model with improved representation of energy crop systems was used to predict the direction and magnitude of environmental impacts associated with plausible biofuel scenarios on hydrology and water quality. In general, the model predicted reduction in stream flow, sediment and nutrient loading at the watershed outlet with perennial bioenergy production scenarios. The results also indicated a need for priority-based, careful planning in bioenergy crop production considering biofuel production potential, environmental impacts/benefits and food/fuel competition. These impacts will result from site, management and biomass system interactions. For example, Scenario 1 where *Miscanthus* is grown on highly erodible land in WCC instead of a corn/soybean rotation, SWAT predicts reduced sediment loading (by 34%) and less organic N (by 23%), organic P (by 24%) and mineral P (by 15%) at the watershed outlet (environmental benefit) with only a modest corn yield reduction of 8% (food) at watershed level and the additional cobenefit of 114 million liters of ethanol. However, when corn stover is removed for feedstock, sediment and organic N losses increased compared to the baseline conditions under conventional tillage system. These trade-offs must be carefully evaluated to meet production and environmental goals.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Location map of Wildcat Creek watershed and St Joseph River watershed. USGS station near watershed outlet is used for model calibration other stations were used for validation.
Appendix S1. SWAT model development, calibration/validation for the study watersheds
Figure S2. Comparison of tile flow with default CN and modified CN (hydrologic soil group one level down). X axis indicates cumulative tile drain area in the watershed.
Table S1. SWAT management inputs for Wildcat Creek watershed
Figure S3. Corn and soybean yield simulation comparison with measured data from NASS county level yield data.
Table S2. SWAT model parameters used for representing tall fescue in the study
Figure S4. Tall fescue simulations of total biomass, leaf area index (top), nitrogen and phosphorus uptake (bottom) for a sample pasture HRU in the watershed
Figure S5. Kentucky bluegrass simulations of total biomass and leaf area index for a sample urban HRU in the watershed.
Figure S6. Sample management file for an urban HRU
Figure S7. Forest simulations of total biomass and leaf area index for a sample HRU in the watershed.
Figure S8. Sample management file for a forest HRU
Table S3. Description of SWAT parameters calibrated in the study and calibrated parameter values
Table S4. Daily and monthly calibration and validation statistics for stream flow in Wildcat Creek watershed
Figure S9. (A-Top left) Scatter plot of observed and simulated daily stream flow.
Figure S10. Corn and soybean yield simulation comparison with measured data from NASS county level yield data.
Table S6. Daily and monthly calibration and validation statistics for stream flow in St Joseph River watershed
Figure S11. (A-Top left) Scatter plot of observed and simulated daily stream flow.
Appendix S2. SWAT model improvements comparison and energy crop parameters
Figure S12. Comparison of improved SWAT model (Trybula *et al*., 2014) with other published SWAT model representations (Blue line: Ng *et al*., 2010; Red line: default model with parameters from Trybula *et al*., 2014).
Table S7. SWAT model parameters used for representing *Miscanthus* (MISC) and switchgrass (SWCH) in the study (adapted from Trybula *et al*., 2014).
Figure S13. Average annual impact of switchgrass based biofuel scenarios on stream flow and water quality at the watershed outlet. (A) Wildcat Creek watershed (B) St Joseph River watershed. Positive value indicates increase in value with respect to baseline scenario.
Appendix S3. Bioenergy scenarios impacts-additional information.
Table S8. Comparison of hydrology and water quality simulation by different landuses in agricultural marginal lands (HRU level) in St Joseph River watershed (scenario 3).
Figure S14. Box plot comparison of difference in nitrate leach (Top: for Scenario1&2) and tile nitrate loading (Bottom: for Scenario 3&4) variability across HRU's in the two study watersheds for perennial grasses compared to corn/soybean rotation.